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SUMMARY PAGE

THE PROBLEM

To determine differences in color appearance within observers over time.

FINDINGS

By measuring the locus of unique blue and unique yellow, minor random-appearing fluctuations in color appearance were seen within observers on a day-to-day basis. Over a period of several months, however, substantial shifts were noted. Sizable differences were also noted between two observers with normal color vision.

APPLICATION

Displays with coding by color identification should use colors sufficiently discriminable that no confusion arises due to shifts of color appearance within an observer or to differences among observers, even if color vision is normal.

ADMINISTRATIVE INFORMATION

This study was conducted at the Walter S. Hunter Laboratory of Psychology, Brown University, Providence, RI as part of Naval Medical Research and Development Command Work Unit M0100.001-5003 -- "Enhanced performance with visual sonar displays." The manuscript was submitted for review on 29 October, approved for publication on 18 December 1987, and submitted to the Optical Society of America. It was published in the Journal of the Optical Society of America A, 1988, Vol. 5, pp. 1983-1985. It has been designated as NSMRL Report No. 1107.

ABSTRACT

To determine differences in color appearance within observers over time, the unique blue and unique yellow loci, points in the spectrum which appear neither reddish nor green, were measured in two observers over a 16-month period. Minor random-appearing fluctuations in color appearance were found for each observer on a day-to-day basis. Over a period of several months, however, substantial shifts were noted. Substantial differences were also noted between the two observers, both with normal color vision. This research indicates that displays with coding by color identification should use colors sufficiently discriminable that no confusion arises due to shifts of color appearance within an observer or to differences among observers, even if color vision is normal.

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Long-term variability in the spectral loci of unique blue and unique yellow

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The spectral loci of both unique blue and unique yellow were measured over a 16-month period. Using the method of constant stimuli, two neutrally adapted observers made forced-choice green or red responses to monochromatic test flashes. Results showed a consistent difference between observers (about 5 nm), considerable within-subject variability (standard deviation 3 nm), and significant long-term drifts (>5 nm) in spectral loci. These results demonstrate the importance of frequently redetermining unique-hue loci when they are used as baselines in chromatic contrast and adaptation studies.

The spectral loci of unique hues are often used as baselines in measuring the effects of chromatic adaptation[1-3] or simultaneous contrast.[4,5] With the general acceptance of the opponent-process model of color perception,[6-10] the role of unique hues in theory and research has taken on an even greater importance. Despite the long-term nature of many experiments, there is, unfortunately, little information on individual differences and intersession variability across extended periods of time. Perhaps the most comprehensive study to date is that of Osaka *et al.*,[11] whose experimental sessions spanned a period of one month. The data in the present paper were obtained for each of two observers over a 16-month period, during observer calibration trials in chromatic contrast[12] research. These data permit examination of individual variability and long-term drift in both unique blue and unique yellow.

METHOD

Apparatus

Two channels of a Maxwellian-view optical system were used. In one channel, light from a 1000-W xenon-arc lamp was projected through a 500-mm Bausch & Lomb grating monochromator to produce the 0.8°-diameter test field. The other channel provided four small, dim xenon white fixation points surrounding the test field. The fixation points remained on continuously, and the test field was flashed by an electronically controlled shutter for 0.5 sec with a fixed intertrial interval of 20 sec. The observer's head position was stabilized by means of a dental impression and a head rest.

Observers

Two male subjects of ages 34 and 45 years with extensive psychophysical experience served as observers. The color vision of both was normal, as determined by the Ishihara pseudoisochromatic plates and the Farnsworth tritan plate.

Procedure

At the start of every session, the output of the test-field channel was set to the desired level by means of a United Detector Technology photometer–radiometer, and the wavelength of the monochromator was calibrated with a narrow-band interference filter. After 10 min of dark adaptation, the observer's red–green equilibrium point for either blue or yellow was determined by the method of constant stimuli, with the observer signaling a forced-choice red or green response to each stimulus presentation. The stimuli, in 1- or 2-nm steps, were presented in random order over a typical range of 10 nm that bracketed the unique-hue point. Five judgments were made at each of the wavelengths, and the "not red, not green" point was determined by linear interpolation of the 50% red–50% green response point.

The illuminances of the stimuli were dictated by the conditions of the primary experiment. For blue and yellow, respectively, the values were 3.0 and 43.7 Td for observer DM and 7.9 and 44.7 Td for observer KL. For each observer the brightnesses of the blue and yellow stimuli appeared similar.

RESULTS

Figure 1 shows the unique-blue loci by session for each observer. The sessions were separated by one- or two-week intervals, except that the first session preceded the others by 10 months. The data show a shift toward shorter wavelengths for DM within an approximately 10-nm range over the 16-month period. Analysis of variance of linear regression showed that the slope of a line fit to the unique-blue locus of observer KL was not significantly different from zero [$F(1, 9) = 0.05$, $p > 0.10$], indicating no shift in locus over time. For DM, however, a significant shift was found [$F(1, 8) = 27.91$, $p < 0.01$]. Except for the first determination, observer KL's unique-blue loci are consistently longer in wavelength than DM's. A rough correspondence between observers in the direction of day-to-day shifts is evident

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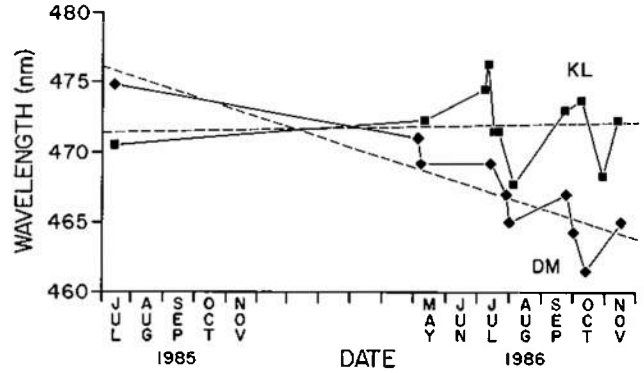

Fig. 1. Unique-blue loci by date for the two observers. The dashed lines are the linear regression functions for each observer's data.

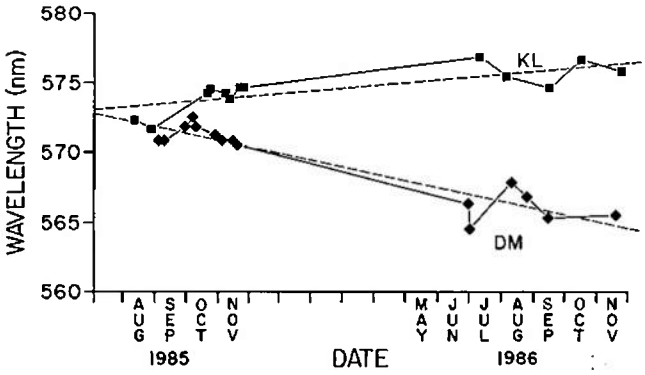

Fig. 2. Unique-yellow loci by date for the two observers. The dashed lines are the linear regression functions for each observer's data.

Table 1. Unique-Hue Loci and Dates of Measurement

Unique Hue	Dates Measured (Month/Year)	Observer	Number of Sessions	Wavelength ± Standard Deviation (nm)	Weighted Mean ± Pooled Estimated Standard Deviation (nm)
Blue	7/85–11/86	DM	10	467.4 ± 3.8	469.8 ± 3.2
		KL	11	472.0 ± 2.5	
Yellow	8/85–11/86	DM	15	569.2 ± 2.8	571.7 ± 2.3
		KL	13	574.5 ± 1.5	

from July through November 1986. Since the observers were tested on different days, it is extremely unlikely that precision of apparatus calibration was the cause of this phenomenon; the effect remains unexplained.

Figure 2 shows the results for unique yellow. The break in data points in each curve represents a seven-month period, December through July, during which no determinations were made. The data collected both before and after that interval are quite uniform for both observers, but general wavelength shifts occurred over that interval, so that the loci were of slightly longer wavelength for KL and shorter for DM than before. All DM's loci before the interval were longer in wavelength than his mean unique-yellow locus, and all were shorter after the interval. Analyses of variance for linear regression showed that, for both observers, significant shifts in unique-yellow locus were found over time: for KL, $F(1, 11) = 17.29, p < 0.01$; for DM, $F(1, 13) = 78.58, p < 0.01$. KL's unique-yellow loci were consistently of longer wavelength than DM's.

Table 1 summarizes the results. The unique-hue loci and standard deviations are close to the values reported previously by others,[11] with the variability in the unique-blue locus being slightly greater than that in the unique-yellow locus. For four observers, Osaka *et al.*[11] obtained standard deviations of 4 nm for unique blue and 3 nm for unique yellow over a one-month period, though no drifts were shown.

DISCUSSION

Results show that an observer can exhibit differences in unique-hue loci as great as 13 nm from session to session over a period of months. Of particular interest is the long-term shift in unique blue and yellow toward shorter wavelengths for DM after a seven-month interval. One possible explanation for intersession variability could be a long-term change in the observer's response criterion. While no data are available that bear directly on this point, examination of the data for each session indicates that the red–green crossover point generally occurred at or about the same wavelength for all five presentations in the range of stimuli. This at least demonstrates intrasession consistency and lack of response bias, therefore making a criterion shift within a session unlikely. Similar consistency was seen with both observers.

Another possible source of variability is related to the Stiles–Crawford effect of the second type[13] (S-C II), whereby light entering the pupil slightly off axis is a different hue from that entering on center. To minimize such effects in this experiment, at the start of each session the observer's pupil was aligned carefully by means of an auxiliary optical channel, using a reticle with crosshairs and concentric rings. Even if the accuracy of this alignment were not sufficient, however, the S-C II effect would be expected to occur randomly and not to give rise to the long-term shifts seen here.

Changes in the apparatus or its calibration were considered as a potential source of the shift in DM's unique-yellow locus, but, as was noted in the Procedure section, the output level and the monochromator wavelength were carefully calibrated at the start of every session. Also, the equipment was regularly in use during the time unique-yellow determinations were not being made. Part of that time was spent in pilot studies and determinations of unique blue, and no changes in the performance of the apparatus were noted. Furthermore, when DM's shift of 4.2 nm in the shortwave direction was observed, the unique-yellow locus of observer KL was determined for comparison. This point was found to be only 2.2 nm from KL's previous unique-yellow locus and, in the long-wave direction, opposite that of DM. These safeguards, then, argue against the possibility of apparatus changes' causing the shift.

Further evidence of the extent of the shift in DM's unique-yellow locus was gained by comparing the psychometric functions for the shortest wavelength before the seven-

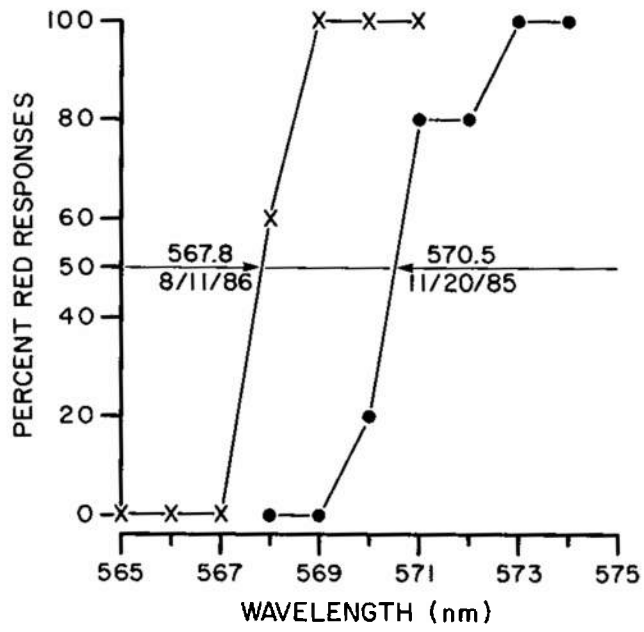

Fig. 3. Psychometric functions of unique-yellow loci for observer DM. Dates sampled are representative of values at the beginning and the end of the experiment.

month interval with the longest wavelength after the interval, in other words, the two closest loci on either side of the interval (Fig. 3). The functions show no overlap; that is, at one intermediate wavelength, 569 nm, 100% of the responses were red before the interval, and 0% were red (100% green) after the interval, although these unique-hue locus determinations were only 2.7 nm apart. The shift in spectral locus therefore appears to be real.

The hypothesis was entertained that seasonal intraocular changes might have occurred. Since the stimuli were monochromatic, a change in the preretinal ocular media would have no effect on hue. However, a seasonal change might have occurred in DM's cone pigment concentration. A reduction in pigment density could produce narrower spectral absorption functions,[14] thereby causing hue shifts. From examining Fig. 2, however, one would have to assume that such a change did not occur the previous year, since the unique-yellow locus was approximately 5 nm higher at the start of the experiment, in September 1985, than after the interruption, in July 1986. DM reported taking no seasonal medications, such as for allergies, which might have had some effect on vision. Additionally, no such change was seen for observer KL.

One final possibility could explain DM's shift in unique-yellow locus, namely, a neural weighting change in the post-receptor pathways. During the interruption in data collection, in December 1985, DM suffered a mild concussion as a result of a whiplash injury. If this injury produced a change in the balance of the neural color pathways, a shift in the unique-hue loci might have resulted. In terms of the opponent-process model,[6] for example, changes in the receptor weighting factors taken 1, 2, or 3 at a time can account for a wide variety of unique-hue shifts, including those found in this study. DM reported taking no new medications after the injury, and, in addition, Fig. 2 shows evidence of DM's shortwave shift even before the injury. The single determination of unique blue before DM's injury indicates a 3.8-nm shift (Fig. 1), also in the shortwave direction, over that period.

In conclusion, these results support the findings of Osaka *et al.*[11] that considerable variability in unique-hue loci exists from session to session. In addition, substantial shifts in color appearance can occur over long time periods. These shifts, especially in the case of observer DM, may not be random short-term fluctuations as Osaka *et al.* (see Ref. 11, p. 185) suggested. This reaffirms the importance of determining unique-hue loci for each experimental session. This precaution will ensure that unique-hue loci can be used as reliable baselines in long-term studies.

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To determine differences in color appearance within observers over time, the unique blue and unique yellow loci, points in the spectrum which appear neither reddish nor green, were measured in two observers over a 16-month period. Minor random-appearing fluctuations in color appearance were found for each observer on a day-to-day basis. Over a period of several months, however, substantial shifts were noted. Substantial differences were also noted between the two observers, both with normal color vision. This research indicates that displays with coding by color identification should use colors sufficiently discriminable that no confusion arises due to shifts of color appearance within an observer or to differences among observers, even if color vision is normal.

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